Final Dawn Reaction Control System (RCS) Propulsion System In-Flight Characterization

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The Dawn spacecraft concluded eleven years of operations on 31-Oct-2018, upon depletion of its hydrazine supply in Ceres orbit during the second extended mission. Dawn's Reaction Control System performed admirably during this lengthy campaign, including years of unanticipated and novel operation given Reaction Wheel Assembly failures during flight. New and modified modes of thruster operations were implemented during the mission. Pressure transducer drift was negligible, consumable limits were generally not exceeded (except for minor violations in Reaction Control System thruster cycles), and thruster performance was nominal throughout this long interplanetary journey. Tank models of hydrazine remaining mass were consistent with depletion within uncertainties, although thruster consumption-based models ended up being conservative by 15%. Unexpectedly, apparent nitrogen permeation through the hydrazine tank elastomer diaphragm allowed hydrazine in the lines below the tank to be pressurized and subsequently utilized during the final days of the mission.

I. Introduction

The Dawn mission was a highly successful Discovery mission to explore the two largest main belt asteroids, *4* Vesta and *1* Ceres. Enabled by ion propulsion, the scientific goals for this lofty and twice-extended mission were to gain insight into the early history of the solar system by studying the largest bodies remaining between Mars and Jupiter after the formation of the solar system. Dawn was launched on September 27, 2007, from Cape Canaveral, Florida, on a Delta II Heavy 2925H-9.5 launch vehicle. A Star-48 upper stage placed Dawn on the initial interplanetary trajectory, with the low-thrust ion propulsion system (IPS) adding orbital energy to enable a Mars gravity assist on February 17, 2009 (see Figure 1 for Dawn's entire heliocentric trajectory). IPS provided an unprecedented 11.4 km/s, enabling the heliocentric transfer from Earth to Vesta via Mars flyby, orbit capture at Vesta, transfer to a low Vesta orbit, departure and escape from Vesta, heliocentric transfer from Vesta to Ceres, orbit capture at Ceres, transfer to low Ceres orbit and back to a high Ceres orbit for potential departure to the asteroid *145* Adeona, and one last transfer to an incredibly low (35-km periapse) final elliptical orbit at Ceres.[1]

Dawn's Reaction Control System (RCS) was simple and conventional, a blowdown hydrazine system with a single spherical, 23-inch diameter, titanium alloy-wall propellant tank with an AF-E-332 elastomer for positive propellant expulsion. Unusually for a JPL-led mission, nitrogen was utilized as the pressurant gas rather than helium, given the sensitivity of one of the instruments to helium. The propellant distribution module incorporated a filter, redundant pressure transducers at the tank outlet, and latch valves separating each of two thruster branches with six small MR-103G thrusters, often referred to as the Rocket Engine Assemblies (REAs). Having both even and odd thruster branches readily available provided redundancy for this lengthy mission. Figure 2 displays a rudimentary view of the Dawn RCS propulsion schematic, and Table 1 summarizes the manufacturer and pedigree for Dawn RCS components.

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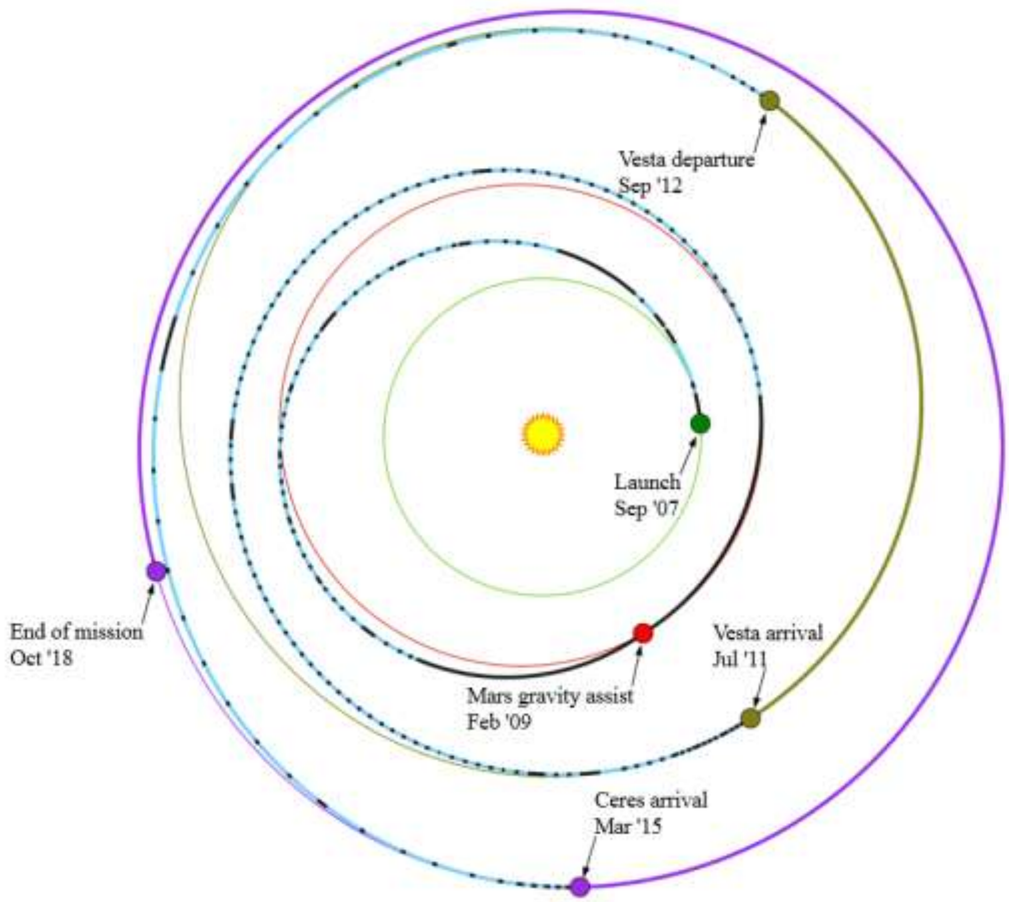

Figure 1. Dawn Heliocentric Trajectory

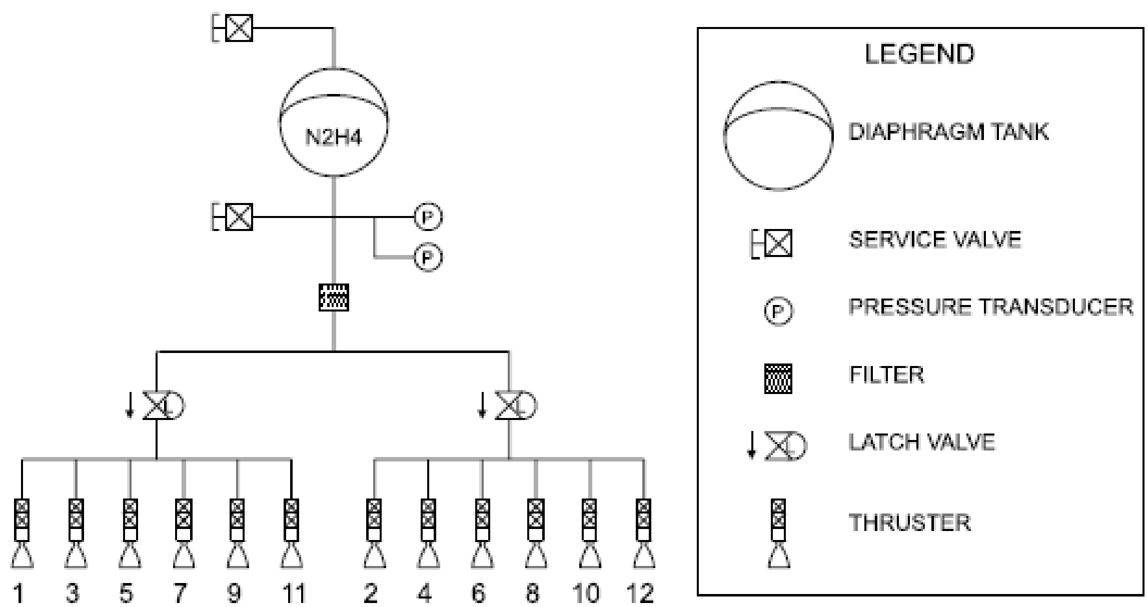

Figure 2: Dawn Reaction Control System (RCS) Schematic

Table 1. Dawn RCS Hardware Component Summary

CPMS Component	Supplier	Flight Heritage / Similarity
Propellant Tank	ATK-PSI (Part # 80274-1)	EXOSAT, VCL, OCO, MSL, TESS, Orbview 3
Rocket Engine Assembly (REA)	Aerojet (MR-103G)	FormoSat-3, SBIRS, Star-2
Low Pressure Latch Valve	Vacco	Numerous spacecraft
Filters	Vacco (Part # F1D10755-01)	Numerous spacecraft
Service Valves	Vacco	Numerous spacecraft
Pressure Transducers	Taber (Model 2403SAT)	Hubble, Fermi, MER, Star-2, Deep Space One

The REAs were located on the Dawn spacecraft as show in Figure 3 in a "folded-out" view. Thrusters on the +X and –X spacecraft faces, when fired in opposing pairs, provided nominally pure coupled moments about the Z axis. Moments about other axes were not pure couples, but rather imparted a net ΔV to the spacecraft. The Dawn navigation team accounted for non-zero RCS ΔV routinely, given the necessity of already having to model low-thrust trajectories during the mission.

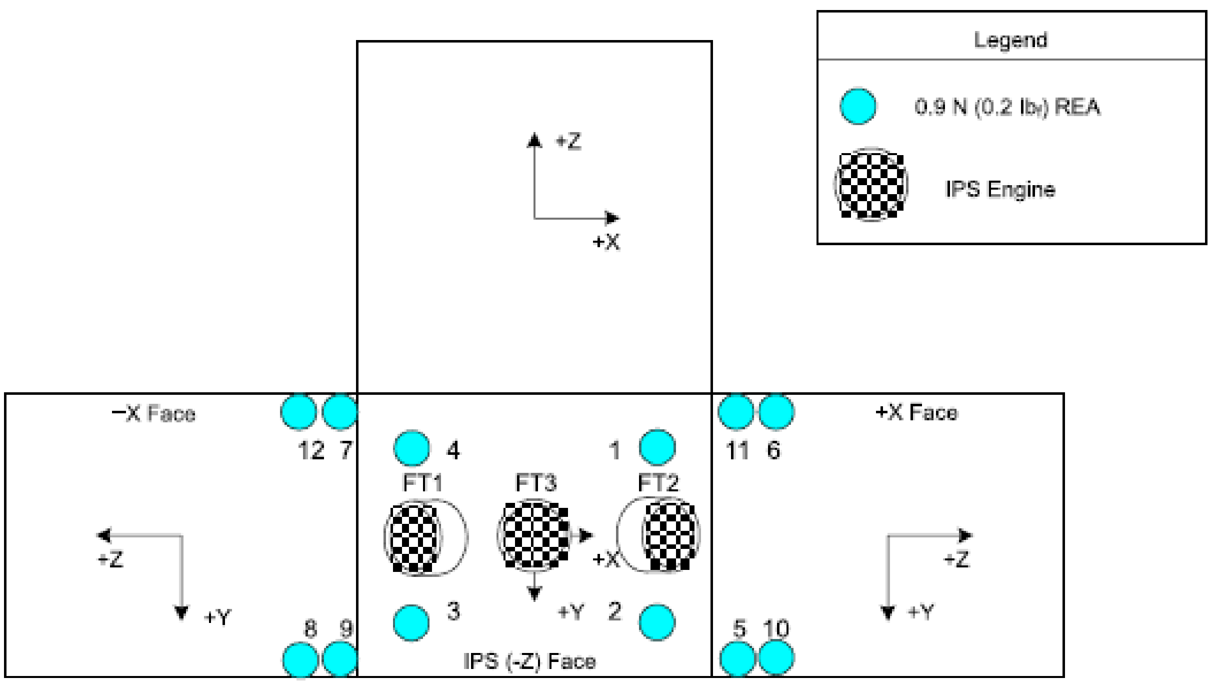

Figure 3: Dawn RCS Thruster Layout, "Folded-Out" Spacecraft View

Table 2 below displays a high-level summary for the entirety of the Dawn mission. Given excellent spacecraft performance (despite unexpected events and anomalies), the mission was able to be extended twice, allowing further detailed studies of Ceres. At both Vesta and Ceres, there were Remote Characterization orbits (RC3), Survey Orbits, High Altitude Mapping Orbits (HAMOs), and Low Altitude Mapping Orbits (LAMOs). Following LAMO at Ceres, the orbit was raised in preparation for a potential departure to the intriguing C-type asteroid *145* Adeona, but eventually it was decided Dawn should remain at Ceres for more detailed observations of the largest dwarf planet in the asteroid belt. In particular, the final elliptical orbit of the mission, XM07, had closest approaches to Ceres every 27 hours at an altitude only three times higher than a commercial airliner flies above the Earth! Indeed, some of the most compelling science of the entire mission was amassed during this final mission phase.

Table 2. Major Dawn Events over the Entire Mission (2007-2018)

Start Date [M/D/Y]	**End Date [M/D/Y]**	**Mission Event**
9/27/2007	---	Launch
2/17/2009	2/17/2009	Mars Gravity Assist
5/3/2011	---	End of Cruise/Vesta Approach
7/16/2011	---	Gravitational Capture at Vesta
7/22/2011	7/25/2011	Vesta Remote Characterization Orbit RC3
8/2/2011	8/31/2011	Vesta Survey Orbit
10/1/2011	11/1/2011	Vesta Initial High Altitude Mapping Orbit (HAMO)
12/12/2011	5/1/2012	Vesta Low Altitude Mapping Orbit (LAMO)
6/15/2012	7/25/2012	Vesta Final High Altitude Mapping Orbit (HAMO)
8/25/2012	8/25/2012	Vesta Remote Characterization Orbit RC4
9/5/2012	---	Gravitational Escape from Vesta & Cruise to Ceres
3/6/2015		Gravitational Capture at Ceres
4/23/2015	5/9/2015	Ceres Remote Characterization Orbit RC3
6/5/2015	7/17/2015	Ceres Survey Orbit
8/18/2015	10/23/2015	Ceres High Altitude Mapping Orbit (HAMO)
12/19/2015	10/5/2016	Ceres Low Altitude Mapping Orbit (LAMO)
10/16/2016	11/4/2016	Ceres XM2 Orbit (1st Dawn Mission Extension)
11/4/2016	6/6/2018	Various Ceres Orbits (Potential Adeona Departure)
6/6/2018	10/31/2018	XM07 Orbit (Final Ceres Close Elliptical Orbit)
10/31/2018	---	Hydrazine Depletion & End of Mission

Another quite useful table is a summary of spacecraft safing events over the eleven-year Dawn mission. Generally, safe-comm was a more benign response, a temporary “stand-down” state which allowed continued communications over the spacecraft high gain antenna. Safe-mode was a more involved fault protection response, including pointing the spacecraft at the sun and rotating it in a so-called “rotisserie” mode before eventually turning back to Earth-point. Most safe-comm and safe-mode events were unplanned, typically due to human error (issues with flight software, spacecraft parameters, or commanding errors), single event upsets (SEUs), or spacecraft hardware anomalies. These further challenged an already stretched flight team trying to fly a most complex Discovery mission to multiple targets. Table 3 summarizes safe-comm and safe-mode entries during Dawn’s entire mission, including the date of the safing, type of event (safe-comm or safe-mode), mission phase, and root cause. Fortunately, safe-mode and safe-comm fault protection responses worked excellently during eleven years in flight, protecting the spacecraft dutifully all while allowing fairly rapid resumption of mission science.

Table 3. Dawn Safe-Comm and Safe-Mode Entries over the Entire Mission (2007-2018)

Date [M/D/Y]	Type	Mission Phase	Root Cause
9/27/2007	Safe-Mode	Check-Out	Planned @ Launch
11/28/2007	Safe-Mode	Check-Out	Planned @ Flight Software (FSW) Installation
1/15/2008	Safe-Mode	Cruise	Single Event Upset (SEU) in Attitude Control Electronics
4/9/2008	Safe-Comm	Cruise	Misconfigured Ion Propulsion System (IPS) parameter
4/9/2008	Safe-Mode	Cruise	Uplink Command Error
2/17/2009	Safe-Mode	Mars Flyby	Flight Software (FSW) bug: management of star tracker
4/13/2009	Safe-Mode	Cruise	Planned @ Flight Software (FSW) Installation
6/15/2010	Safe-Mode	Cruise	Planned @ Flight Software (FSW) Installation
6/17/2010	Safe-Mode	Cruise	**Reaction Wheel Assembly 4 (RWA #4) failure (in safe mode)**
4/11/2011	Safe-Mode	Cruise	Planned @ Flight Software (FSW) Installation
4/13/2011	Safe-Comm	Cruise	Uplink Command Error: non-stop desaturation
6/27/2011	Safe-Comm	Vesta	Single Event Upset (SEU) in IPS latch valve driver
9/22/2011	Safe-Mode	Vesta	Flight Software (FSW) bug: processor overload
12/4/2011	Safe-Mode	Vesta	Uplink Command Error: spacecraft turn too rapid
1/14/2012	Safe-Mode	Vesta	Flight Software (FSW) bug: processor resource conflict
2/22/2012	Safe-Mode	Vesta	Flight Software (FSW) bug: processor overload
8/9/2012	Safe-Comm	Vesta	**Reaction Wheel Assembly 3 (RWA #3) failure**
9/11/2014	Safe-Comm	Cruise	Single Event Upset (SEU) in IPS latch valve driver
9/11/2014	Safe-Mode	Cruise	Flight Software (FSW) bug: Kalman filter divergence
4/24/2015	Safe-Mode	Ceres	Uplink Command Error
7/1/2015	Safe-Mode	Ceres	IPS Flight Thruster #3 (FT3) gimbal failure
1/14/2017	Safe-Mode	Ceres	Flight Software (FSW) bug: attitude knowledge timing
4/21/2017	Safe-Comm	Ceres	**Reaction Wheel Assembly 1 (RWA #1) failure**
10/31/2018	Safe-Mode	Ceres	Hydrazine exhaustion: End of Mission

During the final four years of the mission, after the most recent Dawn RCS mission operations paper (Ref. 2) was written, further anomalies continued to challenge the Dawn team, including safe comm and safe mode entries on 11-Sep-2014 caused by an SEU and a FSW bug, respectively. For each day of lost ion thrusting, the arrival at Ceres was delayed 8-9 days, so extensive efforts to recover the spacecraft and resume IPS operations were undertaken rapidly and successfully. Ceres approach, optical navigation imaging, and orbit capture occurred without incident in early 2015, though the spacecraft entered safe mode on 24-Apr-2015 due to a commanding error.

Following initial reconnaissance orbits RC1-RC3 at Ceres and survey science, Dawn transferred to HAMO between 1-Jul-2015 and 13-Aug-2015, though yet again the spacecraft entered safing, this time on 1-Jul-2015, the first day of the orbital transfer. HAMO executed without incident 18-Aug-2015 through 23-Oct-2015, followed by a flawless orbital transfer to LAMO between 25-Oct-2015 and 7-Dec-2015.

LAMO itself was an intense period between 16-Dec-15 and 31-Aug-2016 at Ceres, with copious hydrazine usage given high gravity gradient torques at low altitude. In the ensuing first extended mission, there was another orbital transfer 08-Sep-2016 to 06-Oct-2016, this time to a higher altitude Juling observation orbit. Most fortunately, the failure of Reaction Wheel Assembly (RWA) #1 did not occur until April of 2017, by which time Dawn was in a much higher orbit about Ceres. The failure of a third Dawn RWA precluded the further use of so-called "hybrid" attitude control (using a combination of RCS thrusters and healthy RWAs), so the remainder of the mission used RCS thrusters exclusively for attitude control. Despite this limitation, a robust second mission extension was planned and executed, perhaps one of the most challenging (and rewarding) undertakings for the Dawn team, all the way through hydrazine depletion on Halloween (31-Oct) of 2018.

II. RCS Consumable Summary

During the lengthy Dawn mission, the primary RCS consumables were monopropellant (hydrazine) and thruster valve cycles, hydrazine throughput per thruster, and “starts” or deep thermal cycles for each thruster. There was also a consumable limit of no more than 12 “cold starts” (with catbed initial temperatures between 10°C and 120°C) per RCS thruster, but these were not an issue in flight since a maximum of one cold start per thruster (during ground testing) occurred. As was mentioned previously, the life limiting consumable for the Dawn mission ended up being hydrazine, though IPS xenon propellant was also nearly depleted during this eleven-year mission.

A summary of the RCS consumable final values at Loss of Signal (LOS) on 31-Oct-2018 is presented below in Table 4. Since the last data playback over Dawn’s High Gain Antenna (HGA) occurred on 26-Oct-2018, final values for thruster valve cycles, throughput, and starts in Table 4 were estimated based on the latest available data five days before hydrazine depletion, incremented by modeled usage projections through the actual end of mission on Halloween.

Numerous RCS thruster branch swaps transpired during the Dawn mission, for various reasons. Some swaps were planned while others were autonomous. Table 5 summarizes the Dawn RCS branch swap history during eleven years of mission operations. Of particular note is the penultimate branch swap, a pre-emptive switch to attempt to equalize worst-case RCS thruster cycle limit violations on the two branches. This final even-to-odd branch swap was delayed a few weeks vs. the optimal swap date determined previously; therefore, Thruster #4 concluded the mission with a few thousand more pulses than Thrusters #7 and #11 (please refer to Table 4). This was as expected.

It is rather surprising that RCS consumables were not more of an issue for Dawn, particularly given two lengthy mission extensions. This is particularly true given Reaction Wheel Assembly (RWA) failures throughout flight, which then put more onus on the RCS thrusters to complete mission objectives.[2] Rather heroic efforts between the Vesta and Ceres encounters enabled mission success at Ceres, and fortunately the final RWA failure in 2017 occurred after the propulsively intensive LAMO at Ceres, a period of heavy fuel usage. Earlier hydrazine conservation efforts are well documented in Ref. 2, and they literally enabled extended mission success at Ceres.

Table 4. Dawn RCS Consumables as of End of Mission (31-Oct-2018)

RCS Consumable	Used thru End of Mission	Lifetime Limit	% Used
N_2H_4 (Monoprop) Mass [kg]	45.3	45.3	100.0%
Thruster #2 Valve Cycles	86831	134673	64.5%
Thruster #4 Valve Cycles	148038	134673	109.9%
Thruster #6 Valve Cycles	86843	134673	64.5%
Thruster #8 Valve Cycles	86361	134673	64.1%
Thruster #10 Valve Cycles	59438	134673	44.1%
Thruster #12 Valve Cycles	62524	134673	46.4%
Thruster #1 Valve Cycles	93686	134673	69.6%
Thruster #3 Valve Cycles	77186	134673	57.3%
Thruster #5 Valve Cycles	40339	134673	30.0%
Thruster #7 Valve Cycles	141339	134673	104.9%
Thruster #9 Valve Cycles	40049	134673	29.7%
Thruster #11 Valve Cycles	141083	134673	104.8%
Thruster #2 Throughput [kg]	6.035	45.3	13.3%
Thruster #4 Throughput [kg]	9.226	45.3	20.4%
Thruster #6 Throughput [kg]	3.798	45.3	8.4%
Thruster #8 Throughput [kg]	4.093	45.3	9.0%
Thruster #10 Throughput [kg]	2.598	45.3	5.7%
Thruster #12 Throughput [kg]	2.552	45.3	5.6%
Thruster #1 Throughput [kg]	5.008	45.3	11.1%
Thruster #3 Throughput [kg]	4.485	45.3	9.9%
Thruster #5 Throughput [kg]	1.797	45.3	4.0%
Thruster #7 Throughput [kg]	5.367	45.3	11.8%
Thruster #9 Throughput [kg]	2.006	45.3	4.4%
Thruster #11 Throughput [kg]	5.169	45.3	11.4%
Thruster #2 Starts	1071	4000	26.8%
Thruster #4 Starts	1965	4000	49.1%
Thruster #6 Starts	1516	4000	37.9%
Thruster #8 Starts	1978	4000	49.4%
Thruster #10 Starts	1152	4000	28.8%
Thruster #12 Starts	1461	4000	36.5%
Thruster #1 Starts	796	4000	19.9%
Thruster #3 Starts	566	4000	14.2%
Thruster #5 Starts	808	4000	20.2%
Thruster #7 Starts	1207	4000	30.2%
Thruster #9 Starts	741	4000	18.5%
Thruster #11 Starts	1223	4000	30.6%

Table 5. Dawn RCS Branch Swap History

Branch Swap	**Date [M/D/Yr]**	**Mission Time [days]**	**Reason for Swap**
Odd-to-Even	9/27/07	1	Post-launch fault due to slow Xe spindown after 3rd stage solid rocket burn
Even-to-Odd	4/13/11	1295	Flight Software (FSW) load caused On-Board Computer (OBC) reset
Odd-to-Even	4/15/11	1297	Commanded swap to even thrusters since they had fewer off-sun constraints
Even-to-Odd	4/27/15	2770	Pre-emptive swap before busy Ceres ops (Thruster #4 at 86% of cycle limit)
Odd-to-Even	10/31/16	3323	Thrusters #7 & #11 at consumable limit of 134673 cycles
Even-to-Odd	8/17/18	3978	Pre-emptive branch swap to equalize worst-case thruster cycle limit violations
Odd-to-Even	10/31/18	4053	Hydrazine depletion in odd-branch fuel lines at EOM leads to safing & swap

III. Pressure Transducer Drift

Many JPL missions (Voyager, TOPEX-Poseidon, and Galileo, to name a few) have experienced linear pressure transducer drift during the course of their multi-year missions.[3] Frustratingly, this phenomenon has befuddled attempts to understand propulsion system behavior, propellant consumption, and maneuver performance during mission operations.

Unfortunately, in the spaceflight environment, there are often no independent reference points to assess actual pressure, so it is impossible to determine which transducers are absolutely drifting, even for multiple sensors measuring the same physical quantity. Despite this limitation, pressure transducer drifts on previous missions were discovered in flight by differencing the output of two, independent sensors that measured the same pressure and seeing how the difference between the two measurements grew over time.

Figure 4 represents the difference of two Dawn RCS tank outlet pressure measurements, telemetry channel B-0277 minus telemetry channel B-0233, as a function of mission time between launch (27-Sep-2007) and the end of mission (31-Oct-2018). In Figure 1, these two pressure sensors may be found between the N_2H_4 tank outlet and the system filter upstream of the branch tee. The difference between these two pressure values was nearly flat vs. time, suggesting Dawn RCS pressure transducers did not drift much at all, even after eleven years.

As listed in Table 1, Dawn RCS pressure transducers were provided by Taber, with flight heritage from Hubble, Fermi, the Mars Exploration Rovers (MER), Star-2, and Deep Space One. Their excellent performance in flight greatly aided RCS propulsion mission operations for Dawn.

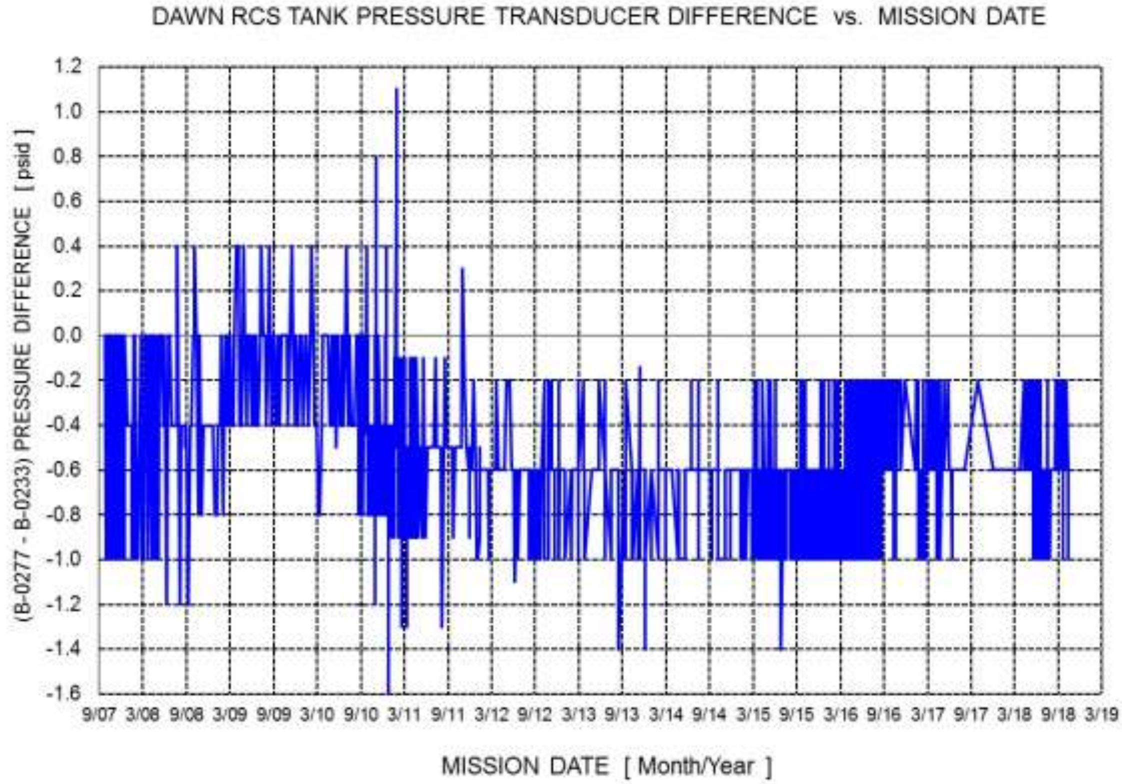

Figure 4: Dawn RCS Tank Outlet Pressure Relative Transducer Drift vs. Mission Time

IV. Hydrazine Mass History

The hydrazine mass remaining between launch and end of mission is displayed below in Figure 5. There are two methods that can be used to estimate spacecraft hydrazine mass remaining. First, a hydrazine consumption model was used to attempt to "bean-count" every drop of hydrazine leaving the spacecraft. This model was of limited use due to the inaccuracies in the pulse-mode consumption model for the thruster, but over short time scales, it was the only way to effectively estimate hydrazine usage for a given propulsive event. For every JPL mission flying this class of thrusters, hydrazine usage has been overpredicted using consumption modeling, which is thankfully in the conservative direction with respect to propellant depletion. An alternative method is to simply calculate the hydrazine mass remaining from telemetered values of tank pressure and temperature using a thermodynamic model (and a known quantity of loaded pressurant gas). This method should offer the greatest accuracy over the long term, as long as pressure transducers are not drifting (as was verified above). The data of Figure 5 were generated using the original pre-launch thruster consumption or "throughput" model with one minor post-launch modification in 2011 to force the consumption and tank models to agree (note well: this correction is within the noise on the scale of the entire mission), along with the thermodynamic or "tank" model.[2] Nearly 3000 hydrazine-consuming events were tabulated over the eleven-year Dawn mission, leading to the fine detail evident in the data of Figure 5.

As anticipated, the consumption model consistently overpredicted hydrazine usage vs. the tank model, over the entire mission. By the end of mission, the original throughput model suggested 45.3 – (-6.8) = 52.1 kg of fuel was expended, or 52.1/45.3 = 115% of the total launch load including unusable hydrazine. However, the more believable tank model indicated only 45.3 - 0 = 45.3 kg of hydrazine was used, or 45.3/45.3 = 100% of the launch load. Equivalently, it appears the original consumption model overpredicted hydrazine usage by (115/100 – 1) =

15% vs. the tank model. This discrepancy is actually very typical; some JPL missions had pulse-mode consumption errors above 30% vs. tank models (e.g., Deep Space One). Cassini MR-103 consumption models also overpredicted hydrazine consumption by almost precisely 15%, albeit for MR-103H thrusters instead of MR-103G thrusters.[4] Consumption modeling errors for very small pulses can be rather sizable, so 15% agreement between the two curves in Figure 5 is actually not too bad at all.

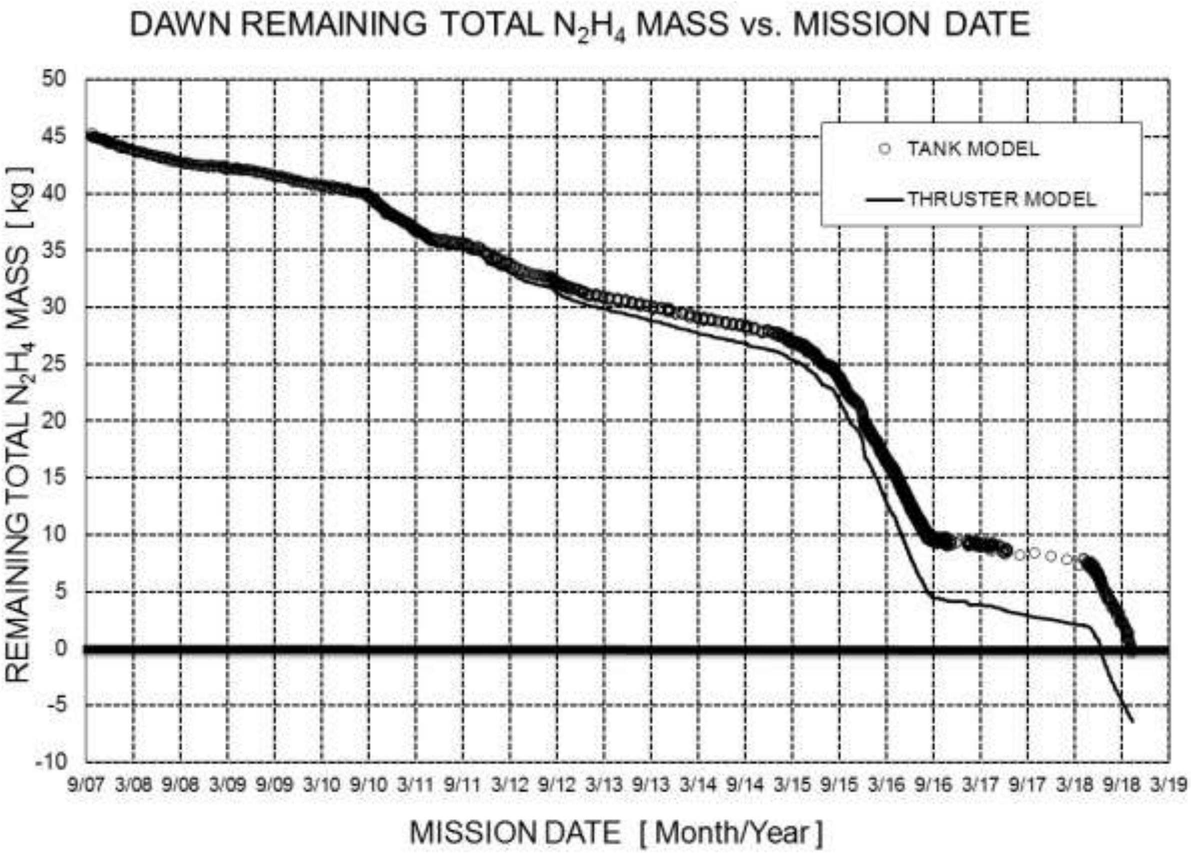

Figure 5: Dawn RCS Remaining Hydrazine Mass vs. Mission Time (Thruster Consumption vs. Tank Models)

It is clear from Figure 5 that Dawn hydrazine usage was not linear vs. mission time. Specifically, during periods of ion thrusting, pitch and yaw control were provided by IPS thruster gimballing, so this reduced hydrazine usage. Even the failure of RWA #3 in August of 2012 did not adversely affect hydrazine usage too much, since this was near the beginning of the orbit transfer to Ceres. It is also evident from Figure 5 and Table 2 that Ceres mapping orbits, particularly HAMO and LAMO, were periods of heavy fuel usage. Without the use of hybrid mode during this portion of the mission (e.g., if another RWA had failed), it may well have been difficult to complete all mission objectives. Thankfully, post-LAMO orbits before the final orbit were sufficiently far from Ceres that RCS operations were feasible. It is clear, though, how rapidly hydrazine was used in the final XM07 orbit, during the last four to five months of the mission.

One of the most gratifying observations from Figure 5 is just how well the tank model matched flight data at the end of mission. In particular, the tank model essentially showed zero remaining hydrazine mass at the point when independent evidence suggested the diaphragm had bottomed out in the propellant tank. This will be discussed in further detail below in Section VI.

V. Dawn RCS Tank Pressure and Temperature History

For archival purposes, it is likely worthwhile to capture plots of Dawn RCS tank pressures and temperatures over this lengthy mission. In particular, future missions may well need to understand as-flown pressure and temperature ranges for the RCS tanks, so these data should be captured for posterity.

Figure 6 below displays the time history of the Dawn RCS tank temperatures. Except for the first few months in flight, the tank equator structure temperature was software controlled over a quite narrow temperature range of 15-17°C, while gas and liquid temperatures were always warmer and more variable, typically spanning a range of 17-24°C. Note also larger fluctuations in temperature for the gas side vs. the liquid side, as expected given its lower thermal inertia.

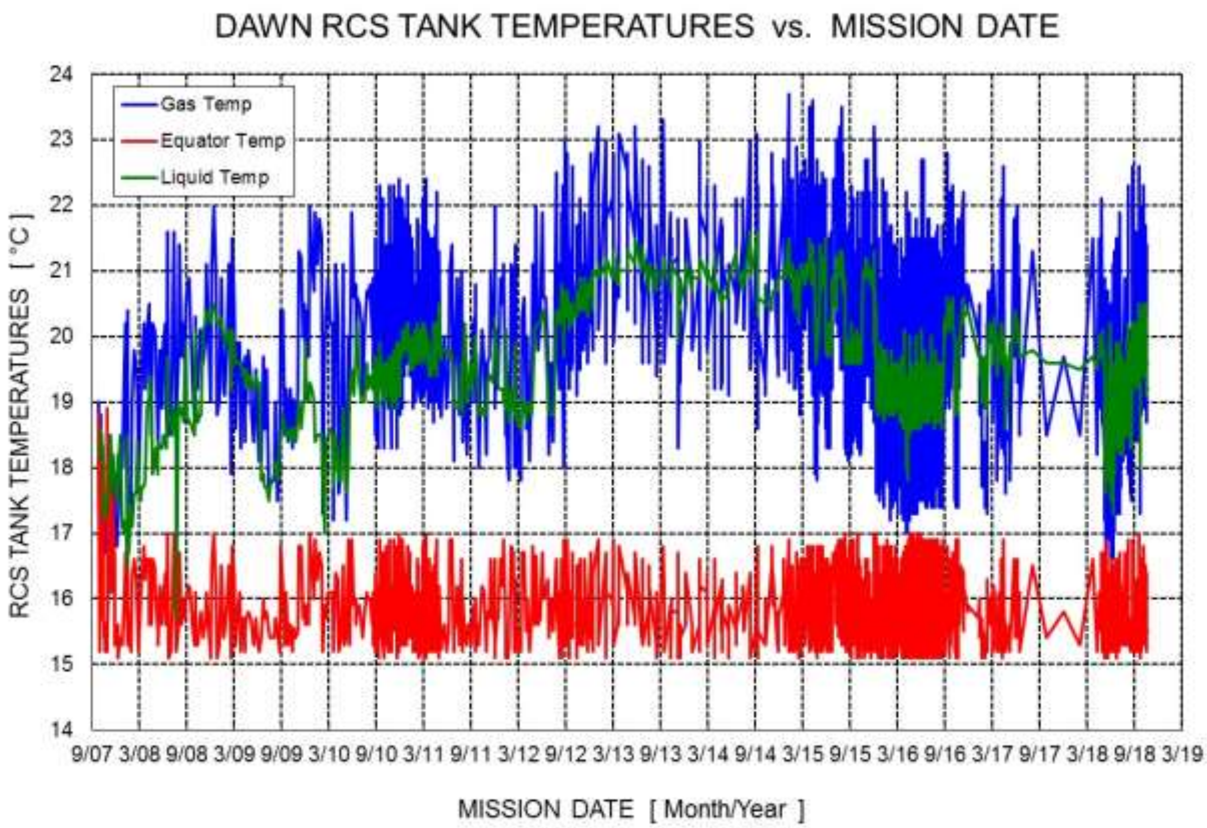

Figure 6: Dawn RCS Tank Temperature vs. Mission Time

Figure 7 presents hydrazine tank outlet pressure over the entire mission, a classic blowdown pressure curve. Note well the measured values from both pressure transducers at the propellant tank outlet (B-0233 and B-0277) agree incredibly well, particularly on this expanded vertical scale (their difference was plotted in Figure 4). The as-flown range for Dawn hydrazine tank pressure was 84-314 psia, securely within the thruster inlet pressure allowable firing range of 70-420 psia. Upon tank depletion, additional thruster firings took place a very low inlet pressures (14-84 psia), though apparently with minimal issues, given the ability of the spacecraft to continue executing its science mission during this time. Line pressure following tank depletion is not shown in Figure 7, so that the data of Figure 7 may be a true representation of tank pressure only over the mission. Line pressures during the final weeks of the mission will be discussed below, in the context of hydrazine exhaustion.

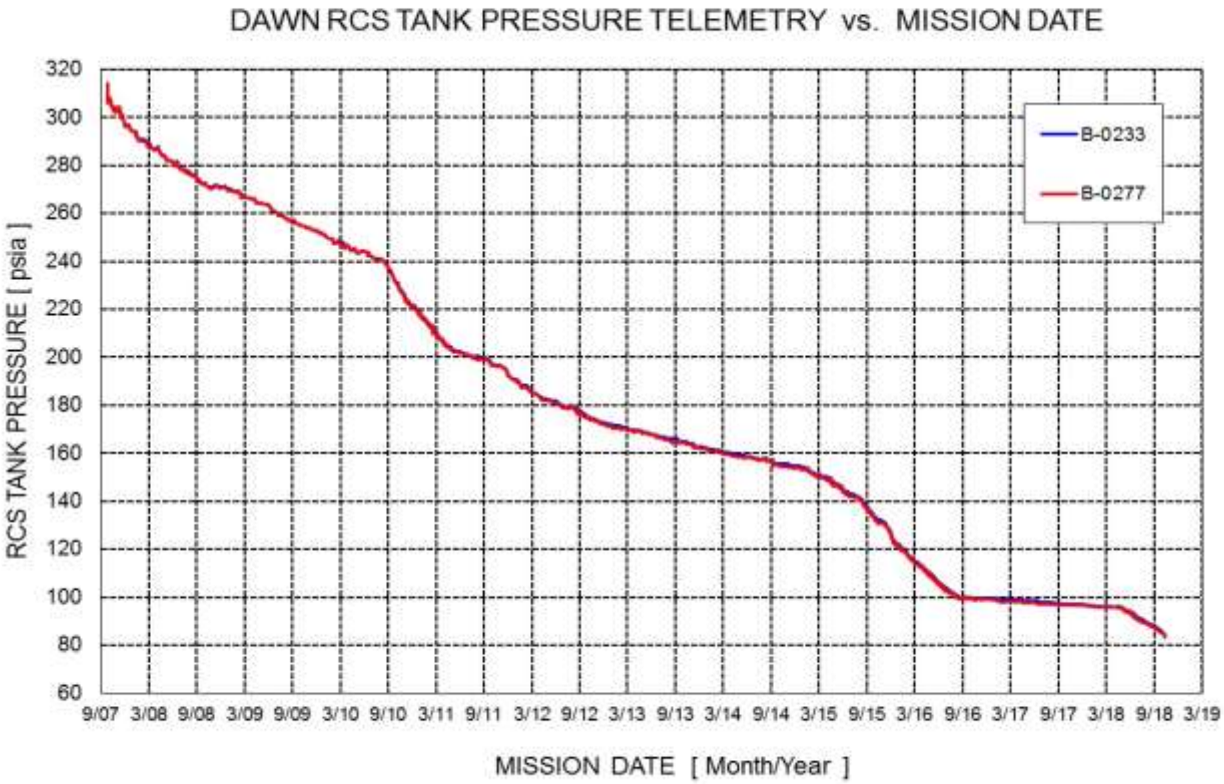

Figure 7: Dawn RCS N_2H_4 Tank Pressure vs. Mission Time

VI. End-of-Mission Thruster Firings after RCS Tank Depletion—an Unexpected Bonus

Initial Depletion

Figure 8 displays RCS tank outlet pressure vs. time just before the end of mission in 2018. Flag 1 on the plot is where the tank diaphragm was expected to bottom out, at a tank pressure of 83-84 psia. Between Flag 1 and 2, hydrazine was being delivered at increasing pressure differential as the diaphragm squeezed the last amount of propellant out of the tank. About 250 grams of hydrazine were used during this period of 5.5 days. This represents 0.4% of the tank capacity, which is consistent with the tank specification minimum expulsion efficiency of 99% and a measured expulsion efficiency of 99.9% during ground testing.

Between Flag 2 and 3 the spacecraft used about 42 grams of propellant during a periapsis pass, followed by 15 grams expelled in a spacecraft turn. These propellant consumption estimates are based on multiplying the thruster model prediction by 0.85. This correction factor is the difference between end-of-life thruster model consumption and the likely much more accurate tank model, as explored above in Section IV.

The model assumes that propellant can be delivered normally up to the point where the maximum amount has been squeezed out of the tank (Flag 2). Thruster commands after that point will result in the line pressure drastically dropping. This results in the nitrogen pressurant gas in hydrazine coming out of solution. Nitrogen is about fifty times more soluble than helium in hydrazine, and this results in gas bubbles being generated throughout the wetted lines. These bubbles can then merge to create larger gas bubbles that stand across the tube cross-sectional area, and this gas pressure allows continued thruster operation.

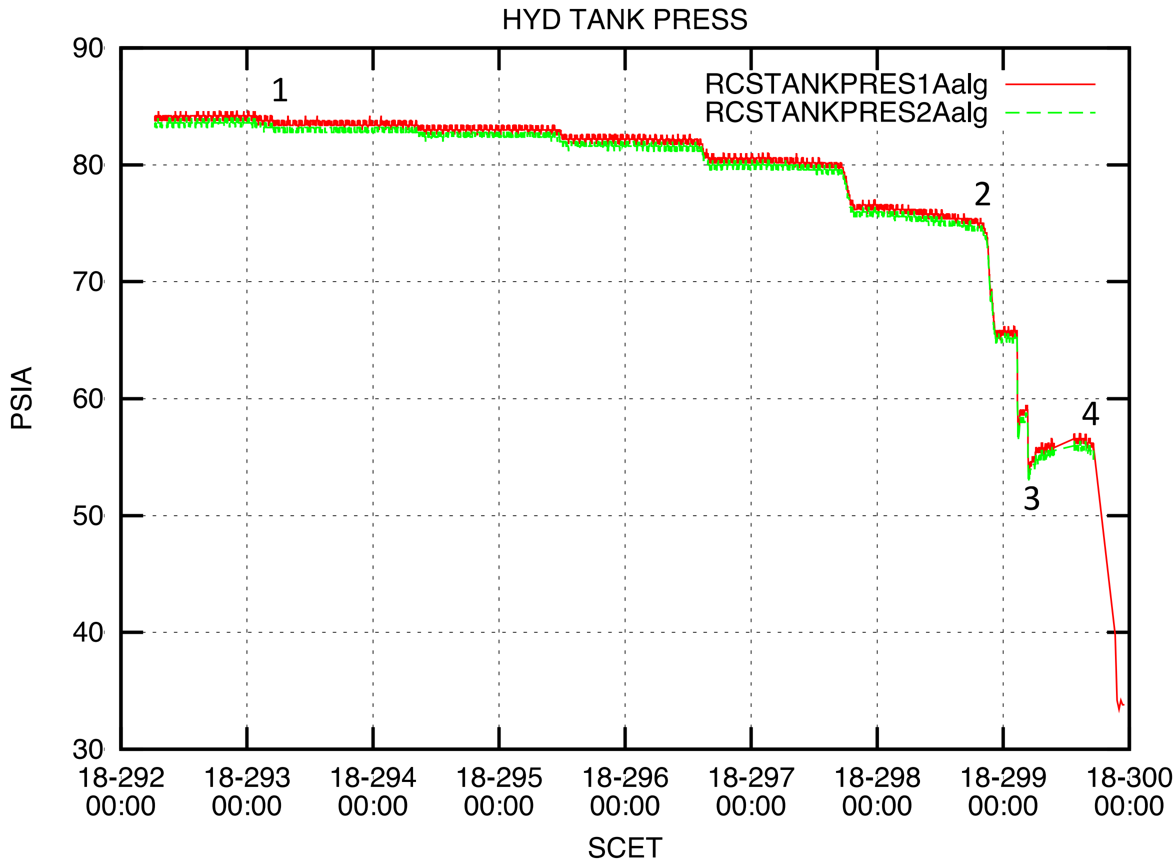

Figure 8: Dawn RCS Tank Pressure during Tank Depletion (2018/292-300 SCET UTC)

Initial gas pocket size

Dawn had its odd thruster branch enabled and the even branch isolated by a closed latch valve during tank depletion. The hydrazine mass in the lines between the tank outlet, odd branch thrusters, and service valve was about 196 grams. Nitrogen solubility in hydrazine is 203 ppm at 1 bar and 25°C. Assuming the hydrazine was saturated at the tank end-of-mission pressure of 84 psia, the total nitrogen in solution may be calculated as 196 grams hydrazine · (84 psia / 14.5 psia) · 203e-06 = 0.231 grams.

If we assume the 54 psia pressure (Flag 3) is the result of gas coming out of solution, and that the gas is in equilibrium, we would expect (84 – 54) / 84 · 0.231 = 0.0823 grams of nitrogen to have come out of solution. The density of N_2 at 54 psia is about 4.34 kg/m^3. The mass of gas coming out of solution would therefore pressurize a volume of 0.0823 / 1000 / 4.34 · 1e6 = 19.0 cc.

The model assumes this 19.0 cc of distributed bubbles feed the thrusters and allow the spacecraft to complete the next periapsis pass and turn. The model also assumes that gas bubbles at Dawn's very low hydrazine flow rates were not expelled through the thrusters (0.9-N thrusters in pulse mode used 21 g/hour for two hours, once every 27 hours). The rationale is the bubbles would be caught by the large propellant filter and by the smaller inlet filters at the thruster valves. Therefore, rather than the gas bubble breaking through the wetted filter element, hydrazine could wick along the wall and around the bubble to and through the filter element.

Diaphragm Leakage

The model assumes the diaphragm will have a fixed pressure differential it can support (like a bubble point) that resists gas leakage from the gas side of the diaphragm to the wetted propellant line side. Examining the period of time between Flag 2 and 3, there is a five-hour period where the line pressure held constant with a 19 psid pressure differential between the tank and line.

After periods of thruster usage, the line pressure dropped to 54 psia and the pressure slowly recovered 2.0 psi over nine hours. This is surmised to be due to leakage of nitrogen across the diaphragm, driven by a pressure differential of 84 psia tank pressure to 54 psia line pressure.

The diaphragm leakage model assumes the diaphragm has a 19 psid "bubble point" with leakage proportional to (tank pressure – 19 – line pressure). Fitting the pressure rise from Flag 3 to 4 and using the 19.0 cc bubble volume sets the diaphragm leak rate as follows: diaphragm leak rate = 0.026 · (84 – 19 – line pressure) scc/hr.

A leakage rate coefficient of 0.026 scc/hr/psi is 2.7% of the expected leakage rate for nitrogen across a dry AF-E-332 rubber diaphragm. This value was obtained by correcting helium leakage rate test data from a smaller tank to Dawn's larger tank size, in addition to making a sonic correction from helium to nitrogen using the square roots of their respective molecular weights. A value of 2.7% for a wetted diaphragm permeation rate after bottoming out the diaphragm seems plausible.

Line Pressure Model

A simple line pressure model was prepared that assumed 42.5 grams of propellant would be used every 27 hours. Starting conditions were set by the preceding estimates: 84 psia tank pressure on the gas side of the diaphragm, 19 psid diaphragm "bubble point", 19.0 cc initial gas bubble volume, and a diaphragm leakage rate coefficient of 0.026 scc/hr/psi set by the 0.22 psi/hr pressure increase seen in data between Flag 3 and 4 in Figure 8.

Model output for Dawn's final few orbits is shown in Table 6. The row labeled "Day 299" sets the initial bubble size and conditions based on the previous estimates. Each of the following intervals models a periapsis pass using 42.5 grams of propellant. Estimates in the fourth column labeled "Line Pressure" can be compared directly with the flight data shown in Figure 9, an extension of Figure 8 now through the end of mission. The dark blue pressure entries in Table 6 are the expected line pressures at the start of the periapsis maneuvers, while the light blue cells in the table show the pressures at the end of the pass.

Pleasingly, the model qualitatively matches the flight data quite well and also explains the flattening of the pressure curve as time goes on. The initial bubble volume of 19.0 cc grows to 61.5 cc and the pressure drops sharply. Leakage across the diaphragm during the interval between passes allows a pressure recovery of about 8 psi. The next periapsis pass expands the bubble volume from 61.5 to 104 cc, and the subsequent pressure decay is substantially less since the volume increase is a smaller fraction of the starting volume. Leakage between periapses increases as the line pressure drops (with more Δp across the diaphragm), but because this leakage is into a larger volume, subsequent line pressure increases are smaller. Incidentally, this model assumes the propellant remains supersaturated with nitrogen after the initial bubble formation.

Figure 9 offers a direct comparison between the flight telemetry data (in blue) and the line repressurization model (in red). For a simple model, the agreement between the two curves is quite good, suggesting the actual physics of hydrazine line depletion have been captured well for Dawn. Most gratifyingly, this unexpected bonus extended the mission an extra one to two weeks. Since each periapsis pass every 27 hours offered additional unique science, this was most appreciated by the Dawn science teams.

Table 6: Dawn RCS Line Pressure Predictions After Tank Depletion, Due to N_2 Diaphragm Permeation

Propellant use per interval (grams)	42.5	Assume thruster model predicts are 15% high			
Tank pressure	84				
Diaphragm Bubble Point (psi)	19				
Diaphragm Leakrate scc/hr/psi	0.026	0.027			
Time interval between prop use (hour)	27.00			**Leak Rate**	**Leak Rate**
	Propellant	**Line**	**Gas in**	**Across**	**Across**
	Used	**Pressure**	**Bubble**	**Diaphragm**	**Diaphragm**
	grams	**psia**	**scc**	**scc/hr**	**psi/hr**
Interval					
Day 299	19	54.00	70.76	0.29	0.22
After Interval Recovery		56.00			
1	61.5	17.30	73.38	1.26	0.30
After Interval Recovery		25.33			
2	104	14.98	107.43	1.32	0.18
After Interval Recovery		19.96			
3	146.5	14.17	143.13	1.34	0.13
After Interval Recovery		17.76			
4	189	13.77	179.42	1.35	0.10
After Interval Recovery		16.57			
5	231.5	13.53	216.00	1.36	0.09

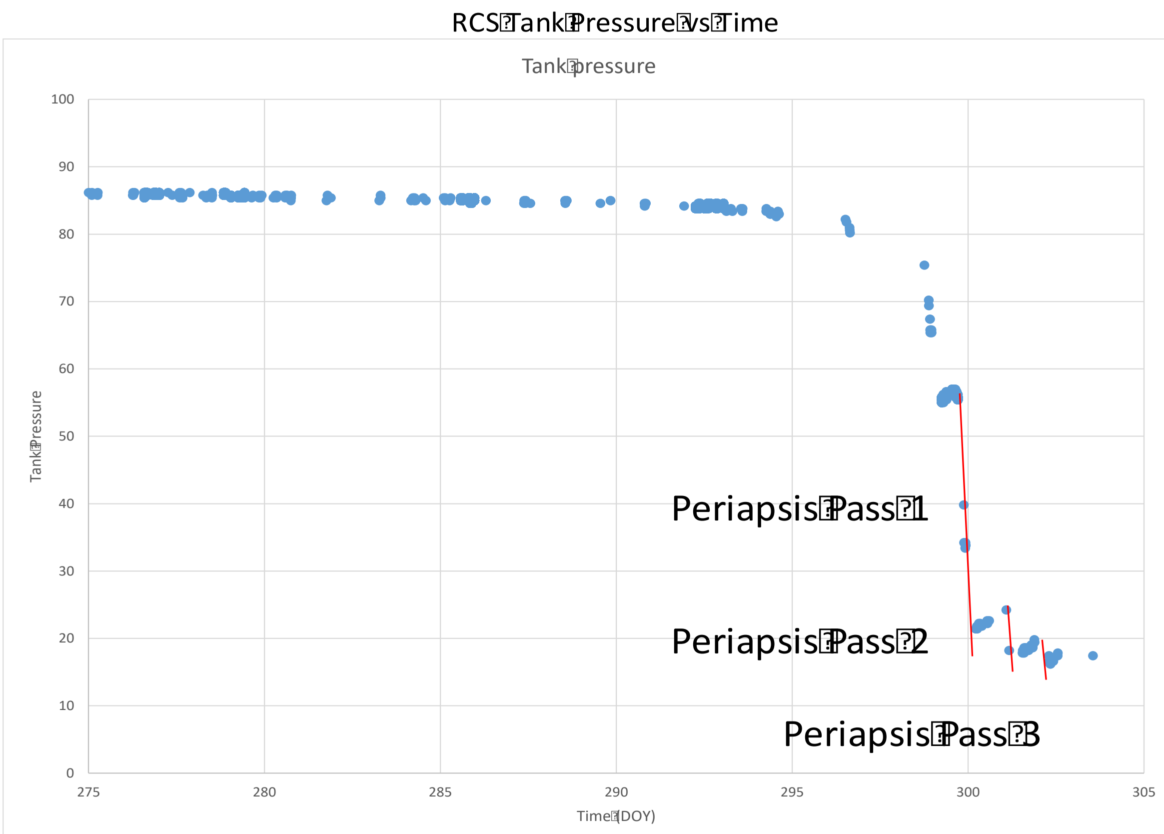

Figure 9: Dawn RCS Line Pressure between Tank Depletion and End of Mission (Actual vs. Model)

Estimated line propellant use

Figure 10 shows a rough estimate of the propellant mass in the Dawn RCS line sections. This is a coarse estimate based on the Hydrazine Tank Assembly drawing. However, even this relatively crude accounting provides reasonable estimates of propellant available from the lines, and it shows a rough match to actual depletion.

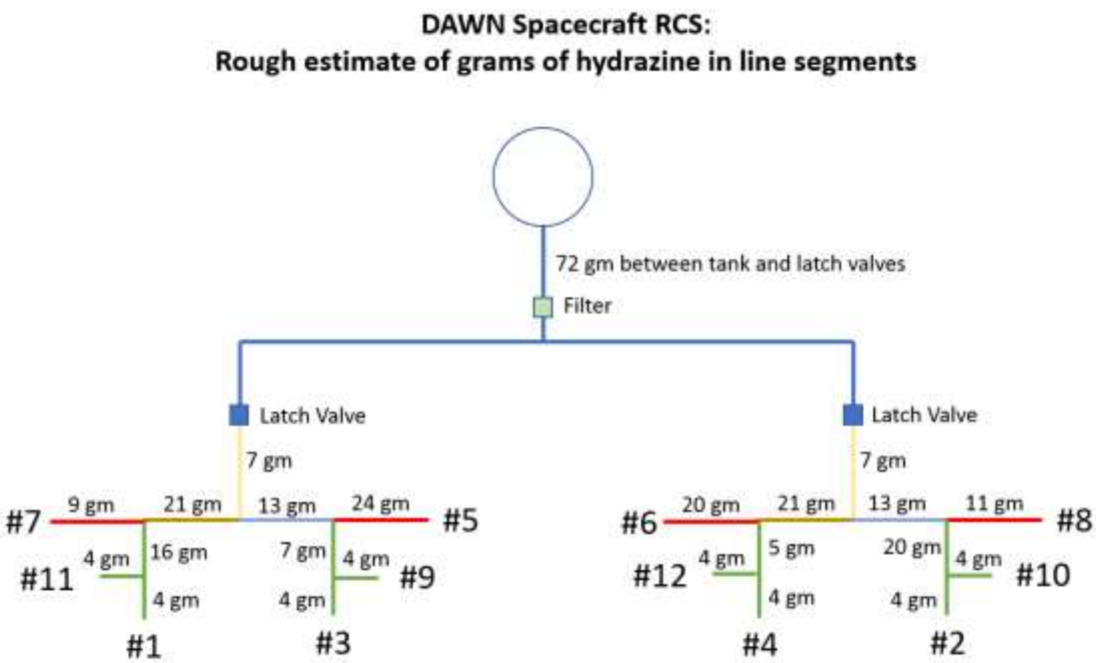

Figure 10: Dawn RCS Rough Estimate of Hydrazine Mass in Line Segments below Tank

The spacecraft operated on the odd thruster branch during the period of line propellant depletion. Over the last six periapsis passes, actual cumulative thruster cycle counts (which were fixed-pulse width counts) are shown in Table 7. These cycle counts have been converted into a "Relative Use" rate in the third column for proper scaling between the different odd branch thrusters, with the least used thruster (#9) assigned a relative use rate of 1.00.

Table 7: Dawn RCS Odd Thruster Branch Use during Final Six Periapse Passes

Thruster #	Pulse Count	Relative Use
1	1220	3.23
3	1119	2.96
5	512	1.35
7	443	1.17
9	378	1.00
11	446	1.18

Examining thruster use and line capacity, Thrusters #3 and #9 were expected to deplete first (24 grams of propellant available past the common tee at a "Relative Use" of 3.96 vs. 41 grams available past the common tee at a "Relative Use" of 4.41). Allocating propellant utilization based on the "Relative Use" table allows reconstruction of the mass of propellant available to thrusters #3 and #9 at depletion. Table 8 shows usable propellant mass as well as the amount of total propellant capacity in the line sections.

Table 8: Estimated Dawn Hydrazine Line Propellant Available at Depletion

		Propellant Burned (grams)	Line Capacity (grams)
Tank to LV (grams)		72	72
Branch commons (grams)		7	7
3, 5, 9		13	13
3		11	11
5 Leg		4	24
9 Leg		1	4
1, 7, 11		29	53
Propellant migration from less used to high use lines		14	
Total Burned at depletion of #3 & #9		**151**	**184**

Estimated propellant available to Thrusters #3 and #9 based on line capacity is 137 grams. If we assume gas bubbles move and merge at the thruster inlet filters, those initial bubbles would be at 54 psia. Diaphragm leakage would increase the line pressure by adding gas to the bubble under the tank diaphragm. This would compress the bubbles at the thruster inlets. Thruster use during the next periapsis pass would then drop the line pressure to about 20 psia as propellant is used. Expansion of the bubbles from lesser used thrusters would push propellant from the lesser used lines into the line sections of the higher use thrusters. This would then provide additional propellant to the high use thrusters.

A rough estimate of 7 grams of propellant could be extracted from the line sections of Thruster #5 and #9. This would allow another 7 grams to be used by thrusters #1, #7, and #11 so that the propellant available through the odd branch would be about 151 grams in total.

These models predict the spacecraft would be able to support three periapsis passes after Day 299's maneuvers, which would prolong the mission to Tuesday, 30-Oct-2018. Depletion of the odd thruster branch would then take place during the Wednesday (Halloween) periapsis pass, which matched observations precisely.

Swap to Even Thruster Branch

The even thruster branch was isolated from the tank late in the mission, occurring when the tank was at 90 psia in August of 2018 (see Table 5). The sequence for swapping branches opens the even latch valve while the odd latch valve is still open, followed by closing the odd latch valve two seconds later. When the even latch valve was opened for the final time (after depleting odd branch hydrazine on 31-Oct-2018), gas came out of solution as the line pressure dropped from 90 psia to under 20 psia. Assuming the pressures equalized, the gas coming out of solution should have increased the line pressure roughly 8 psia. Propellant from the even branch could have then moved into the common line or into the odd branch lines as gas bubbles merged and expanded to equalize the line pressures.

This makes it difficult to determine how much propellant might have been available for use after the branch swap. Line pressure in the odd branch at swap is also unknown, since the spacecraft could have expelled gas prior to swapping branches. If the swap took place without losing much gas, we would expect the line pressure to have increased and thruster operations should have remained possible on the even branch.

Telemetry indicated the spacecraft successfully swapped branches and continued operations for a limited time. Prior periapsis passes on the even branch showed Thruster #4 the most heavily used. Branch depletion would be similar to the odd branch after roughly 70 to 80 grams of propellant use.

To calculate the maximum ΔV imparted after branch swap (caused by entering safe-mode), a conservative estimate for the maximum propellant used would be to assume the spacecraft was able to expel all the remaining propellant from the lines to the thrusters. This would be 300 grams (maximum available in lines) – 137 grams (minimum used prior to swap) = 163 grams. As such, this should constrain the worst-case ΔV perturbing the final orbit, for navigation modeling purposes.

Lessons Learned

From this surprising experience on Dawn, propellant trapped under the tank diaphragm may be used under certain conditions to support operations after the tank diaphragm bottoms out. This was likely enabled by the choice of nitrogen gas, the ability to operate with very low flow demand, and the extended quiescent periods between thruster firings in the final elliptical orbit. Dawn's final orbits only used 42 grams of propellant during each 27-hour orbit, largely concentrated at periapsis.

Nitrogen is about fifty times more soluble in hydrazine than helium, and this created large bubbles in the lines when thruster valves were opened with the diaphragm bottomed out. In fact, it produced a bubble seven times larger than helium would have generated. These bubbles were large enough, and at a high enough pressure, to support continued thruster operations.

Future missions seeking to maximize propellant utilization could select the thruster branch for terminal operations based on thruster use and propellant volumes in the line segments. The spacecraft could then open both latch valves prior to the diaphragm bottoming out. Having all the propellant de-gas at once would generate the largest amount of gas, increasing the chance for recovered operations. It would also minimize a second degassing event upon swapping thruster branches.

Shortly after gas coming out of solution allows line pressure recovery, the isolation valve to the unused thruster branch could be closed to stop propellant moving from branch to branch as propellant is depleted from the active branch. A model would have to be developed to regulate the use of the two branches to maximize propellant utilization. This would likely require intentionally swapping branches as propellant was consumed so that roughly equal line pressures could be maintained in both branches. Of course, this would need to be traded against the mission risk of multiple branch swaps. Still, it is quite remarkable how Dawn managed to use nearly every drop of hydrazine loaded on the spacecraft, much to the delight of project engineers and scientists.

VII. Conclusions

The Dawn mission was a resounding success, delivering groundbreaking science on a Discovery-class budget. The spacecraft performed spectacularly during the prime mission and two extended missions, despite the challenges of losing three reaction wheels and facing other in-flight anomalies. Dawn's RCS performed exquisitely during the mission, through and including hydrazine depletion. RCS thruster performance was nominal despite minor violations of consumable limits, tank pressure drift was non-existent, and hydrazine thought trapped in the lines below the propellant tank allowed bonus operation during the last week or two of the mission.

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References

[1] Rayman, Marc D.; Fraschetti, Thomas C.; Raymond, Carol A.; and Russell, Christopher T.: "Preparing for the Dawn Mission to Vesta and Ceres," 10.2514/6.IAC-05-A3.5.B.01, 56th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law, 2005.

[2] Mizukami, M. and Nakazono, B.: "Dawn Spacecraft Reaction Control System Flight Experience," AIAA Paper 2014-3591, July 28-30, 2014.

[3] Barber, Todd J.; Krug, F. A.; and Renner, K. P.: "Final Galileo Propulsion System In-Flight Characterization," AIAA Paper 97-2946, July, 1997.

[4] Barber, Todd J.: "Final Cassini Propulsion System In-Flight Characterization," AIAA Paper 2018-4546, 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, August 19-22, 2018, Indianapolis, IN.